Santa Fe, July 14, 2005

Life and Death of Pop III Stars

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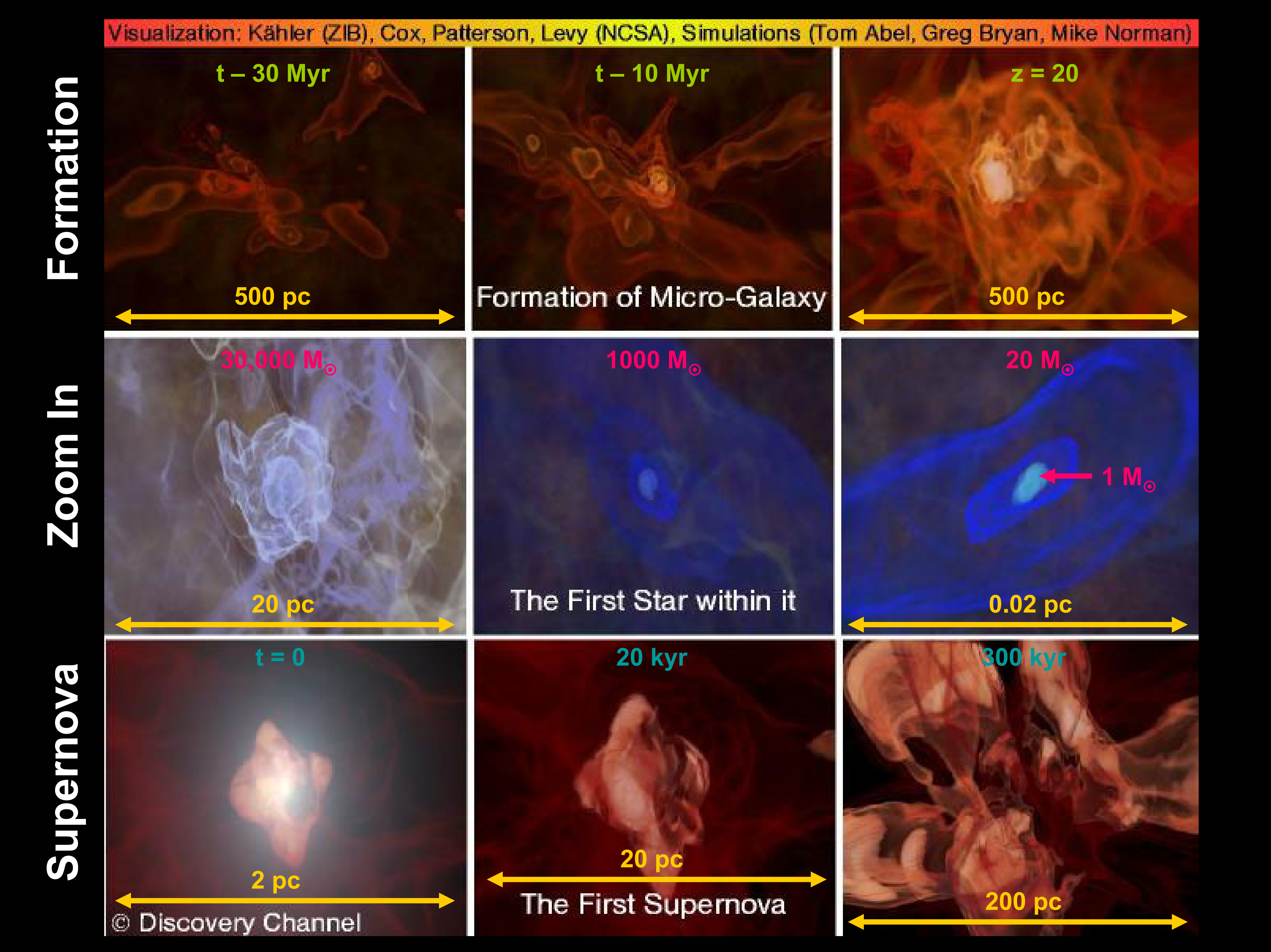
Overview

- Basics of massive star evolution and nucleosynthesis
- Birth, life, and fate of Pop III stars
- Nucleosynthesis in *very massive* Pop III stars (100–1000 $M_\odot$)
- Nucleosynthesis in *massive* Pop III stars (10–100 $M_\odot$)
- Other way to blow up massive stars



Visualization: Kähler (ZIB), Cox, Patterson, Levy (NCSA), Simulations (Tom Abel, Greg Bryan, Mike Norman)
Formation
Zoom In
Supernova
t – 30 Myr
500 pc
t – 10 Myr
Formation of Micro-Galaxy
z = 20
500 pc
30,000 $M_\odot$
20 pc
1000 $M_\odot$
The First Star within it
20 $M_\odot$
1 $M_\odot$
0.02 pc
t = 0
2 pc
© Discovery Channel
20 kyr
20 pc
The First Supernova
300 kyr
200 pc

IMF of the First Stars

Predicted to be heavy to very heavy

by theory – insufficient cooling due to lack of metal (e.g., Larson 1999)

and by numerical simulations

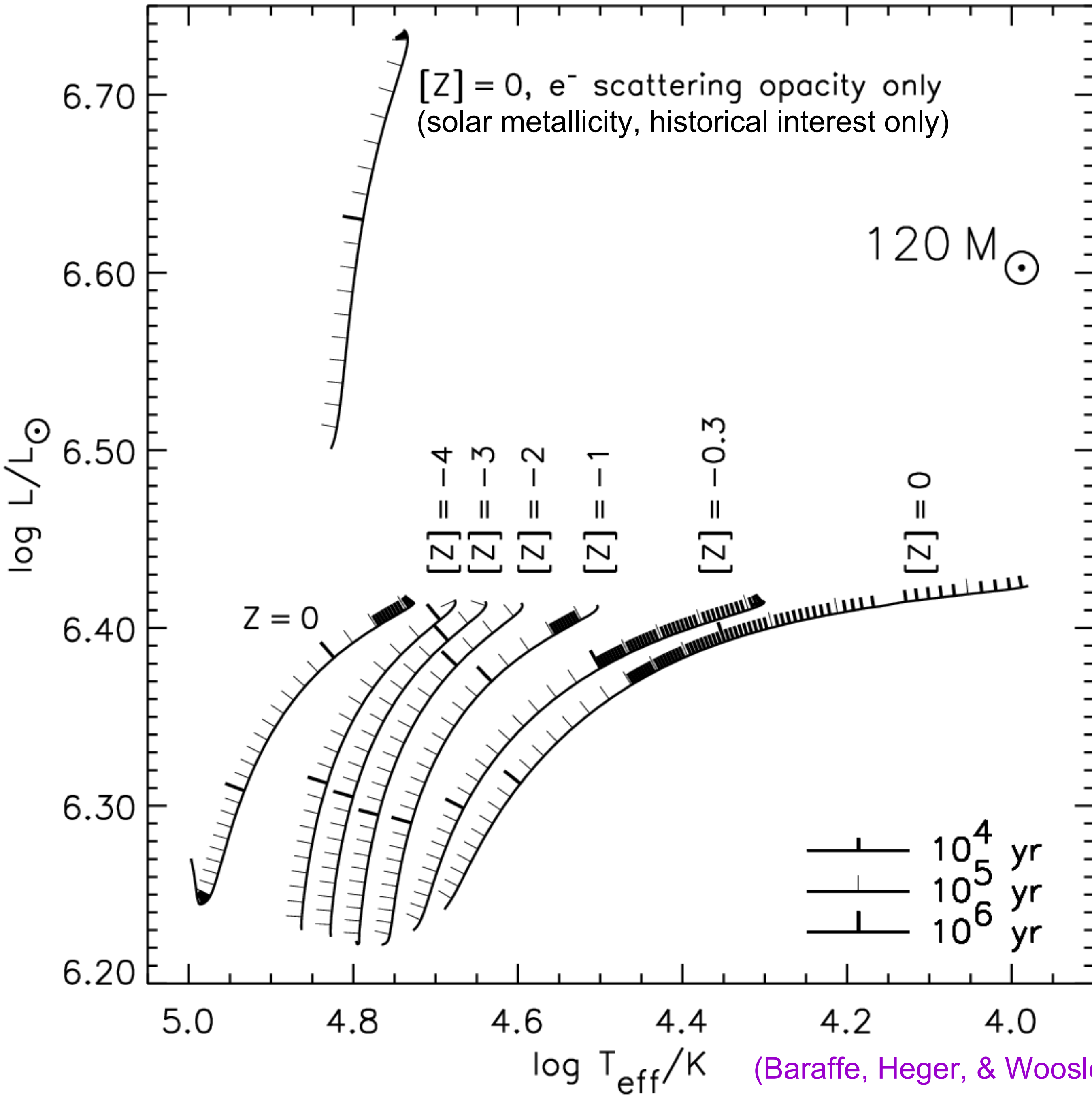
(Bromm, Coppi, & Larson 1999, 2002;

Abel, Bryan, & Norman 2000, 2002;

Nakamura & Umemura 2001)

with a typical mass scale of ~100 $M_\odot$

➔ **The first stars *may* have had a significant very massive population**

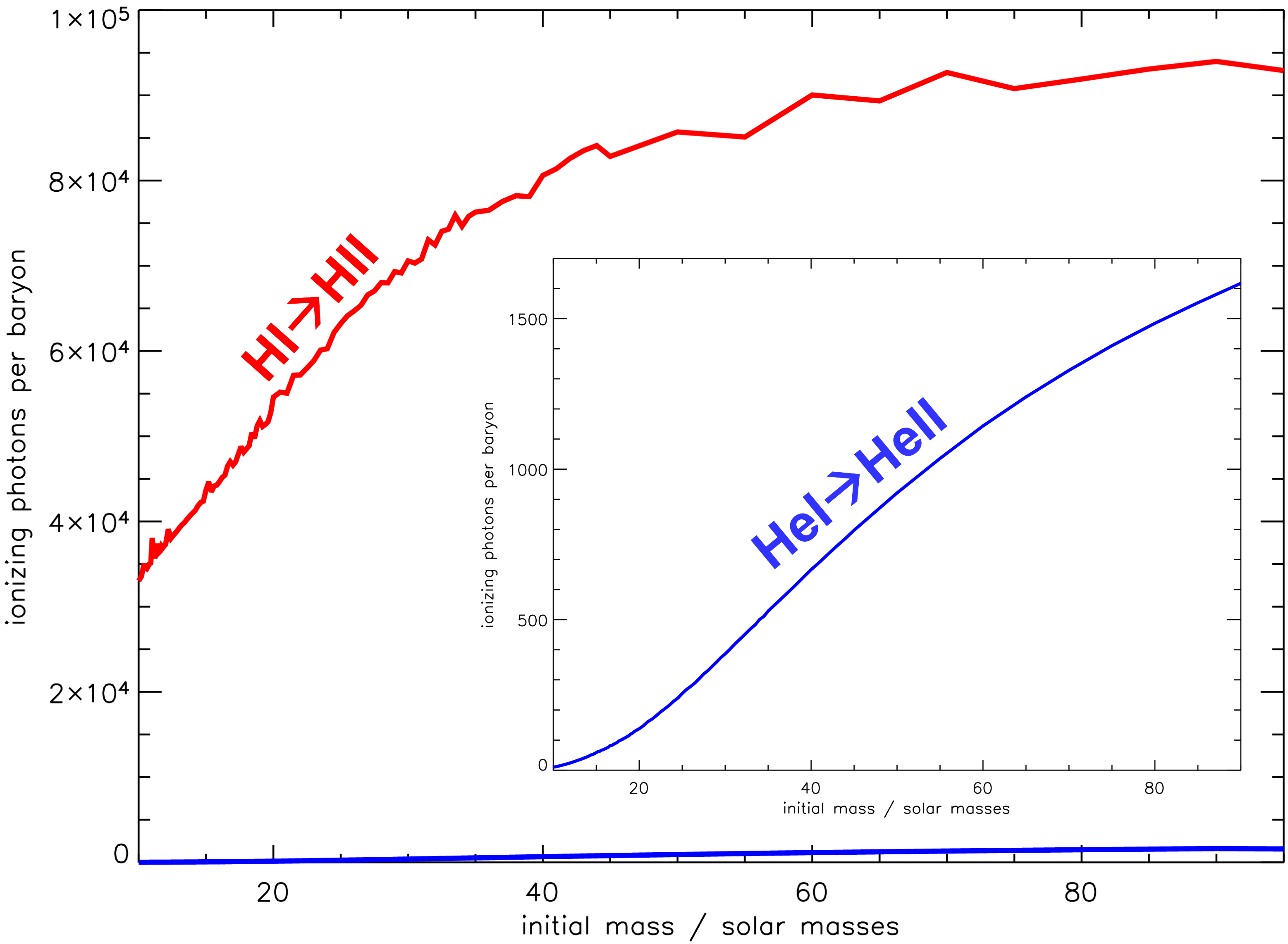


Higher effective temperature for lower initial metallicity

➔ more ionizing photons

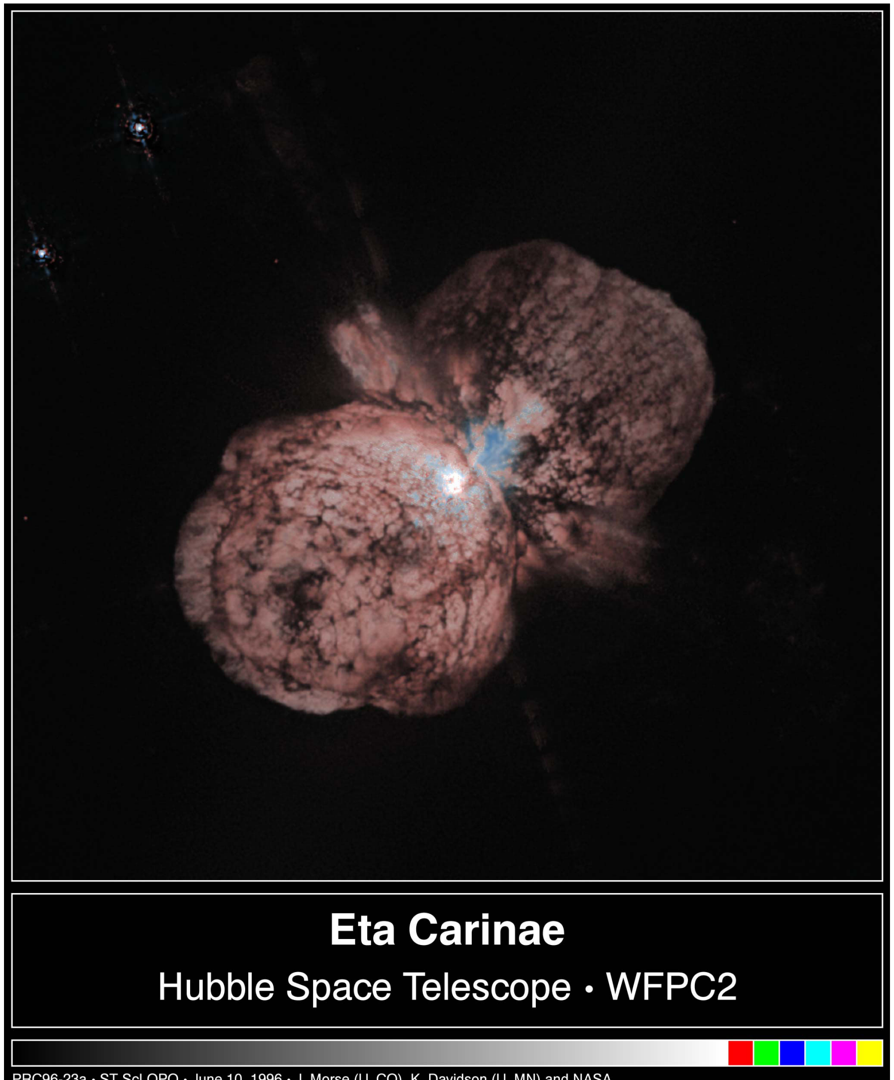
(Baraffe, Heger, & Woosley 2001)

Ionizing Photon Fluxes



The number of ionizing photons per baryon strongly depends on the initial stellar mass at low mass, but levels off at high stellar mass (constant stellar temperature).

Additional Ingredient



Essentially negligible mass loss in Pop III stars

in contrast:

Eta Carina

- Galactic star / solar+ metallicity
- Extremely high mass loss rate
- Initial mass: 150-200 $M_{\odot}$ (?)
- Will likely die as much less massive object

Mass Loss in Very Massive Primordial Stars

- Negligible line-driven winds
  (mass loss ~ metallicity$^{>1/2}$ – Kudritzki 2002)
- No opacity-driven pulsations (no metals – Baraffe, Heger & Woosley 2001)
- Continuum-driven winds @ $L \sim L_{Edd}$ have to be explored
  (Owocki, Shaviv, *et al.*)
- Epsilon mechanism inefficient in metal-free stars below ~1000 $M_\odot$
  from pulsational analysis we estimate:
  - 120 solar masses: < 0.2 %
  - 300 solar masses: < 3.0 %
  - 500 solar masses: < 5.0 %
  - 1000 solar masses: < 12. %

  during central hydrogen burning
- Red Super Giant pulsations could lead to significant mass loss during helium burning for stars above ~500 $M_\odot$
- Rotationally induced ***mixing*** and mass loss?

Nuclear burning stages

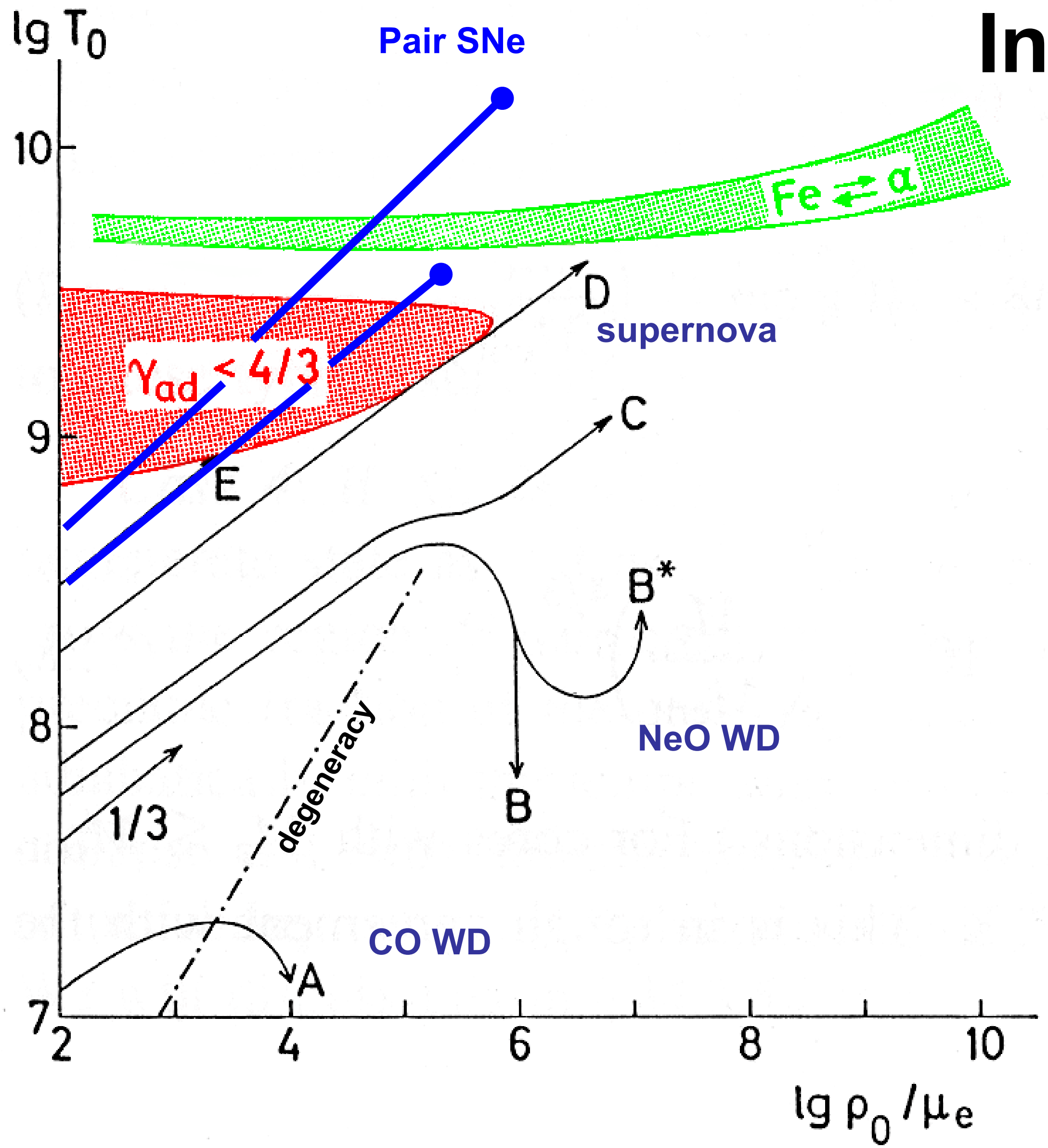
Burning stages		20 $M_\odot$ Star		200 $M_\odot$ Star	
Fuel	Main Product	T (10^9 K)	Time (yr)	T (10^9 K)	Time (yr)
H	**He**	**0.02**	**10^7**	**0.1**	**2×10^6**
He	**O, C**	**0.2**	**10^6**	**0.3**	**2×10^5**
C	**Ne, Mg**	**0.8**	**10^3**	**1.2**	**10**
Ne	**O, Mg**	**1.5**	**3**	**2.5**	**3×10^{-6}**
O	**Si, S**	**2.0**	**0.8**	**3.0**	**2×10^{-6}**
Si	**Fe**	**3.5**	**0.02**	**4.5**	**3×10^{-7}**

Explosive Nucleosynthesis

in supernovae from massive stars

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (s)	Main Reaction
Innermost ejecta	*r*-process	-	>10 low Y_e	1	(n,γ), β^-
Si, O	^{56}Ni	iron group	>4	0.1	(α,γ)
O	Si, S	Cl, Ar, K, Ca	3 - 4	1	$^{16}O + ^{16}O$
O, Ne	O, Mg, Ne	Na, Al, P	2 - 3	5	(γ,α), (α,γ)
		p-process ^{11}B, ^{19}F, ^{138}La, ^{180}Ta	2 - 3	5	(γ,n)
		ν-process		5	(ν, ν'), (ν, e^-)

Instability Regimes



Kippenhahn & Weigert (1990)

adiabatic index < 4/3

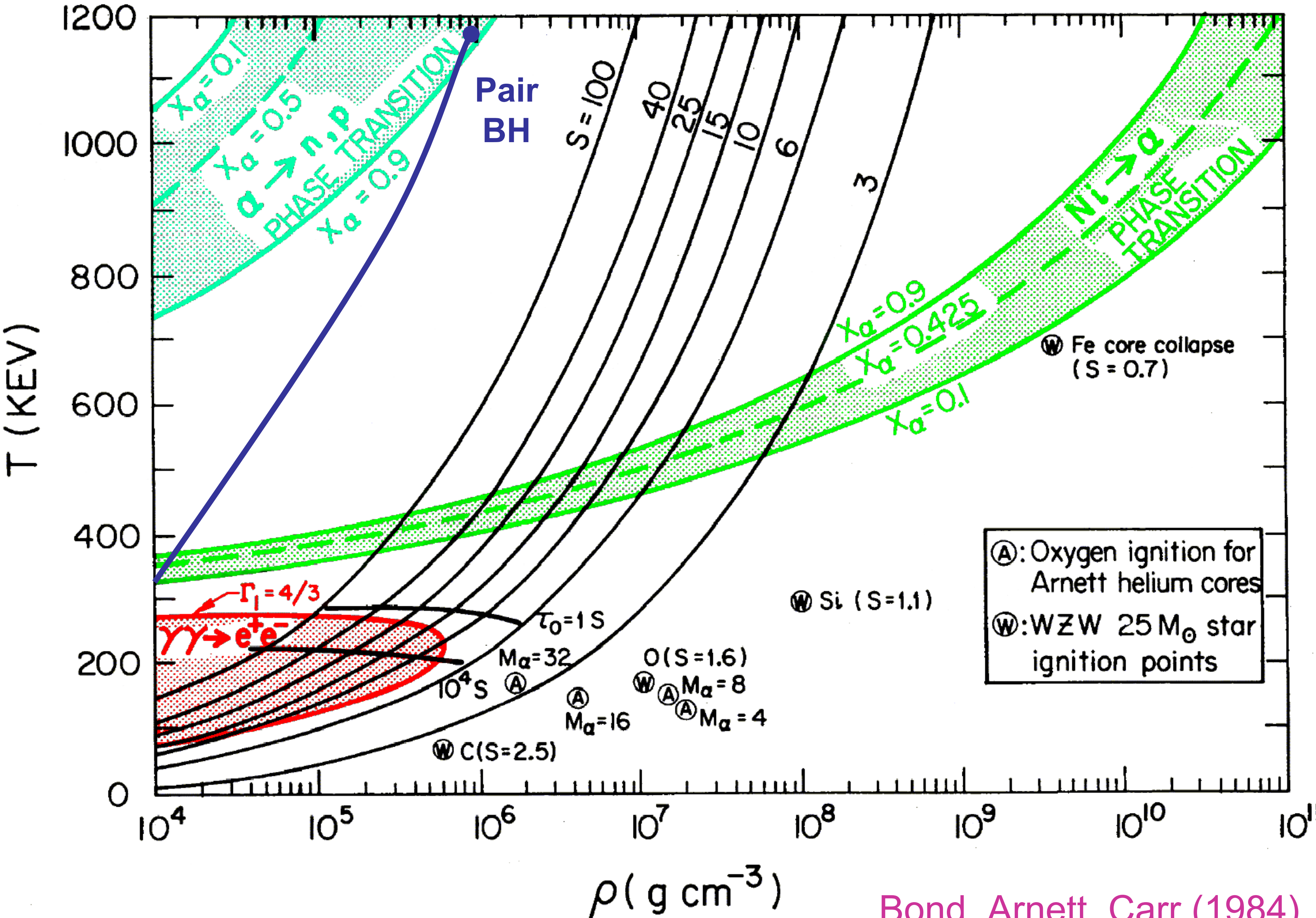
Compression does not result in sufficient increase in pressure (gradient) to balance higher gravity at lower radius

e^+/e^--Pair Instability

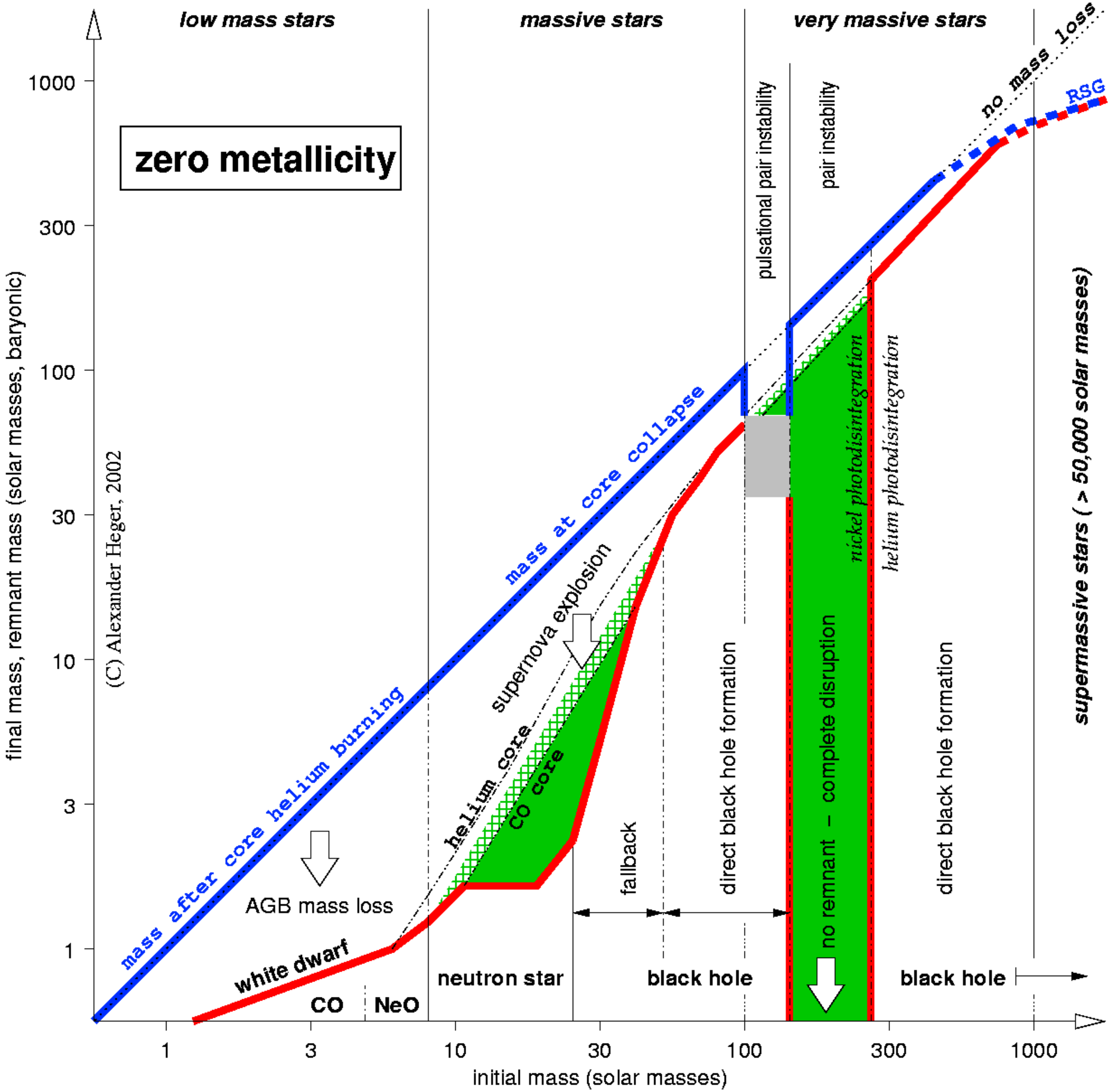
Internal gas energy is converted into e^+/e^- rest mass (hard photons from tail of Planck spectrum)

Photo disintegration

Internal gas energy is used to unbind heavy nuclei into alpha particles and at higher temperature those into free nucleons



Bond, Arnett, Carr (1984)

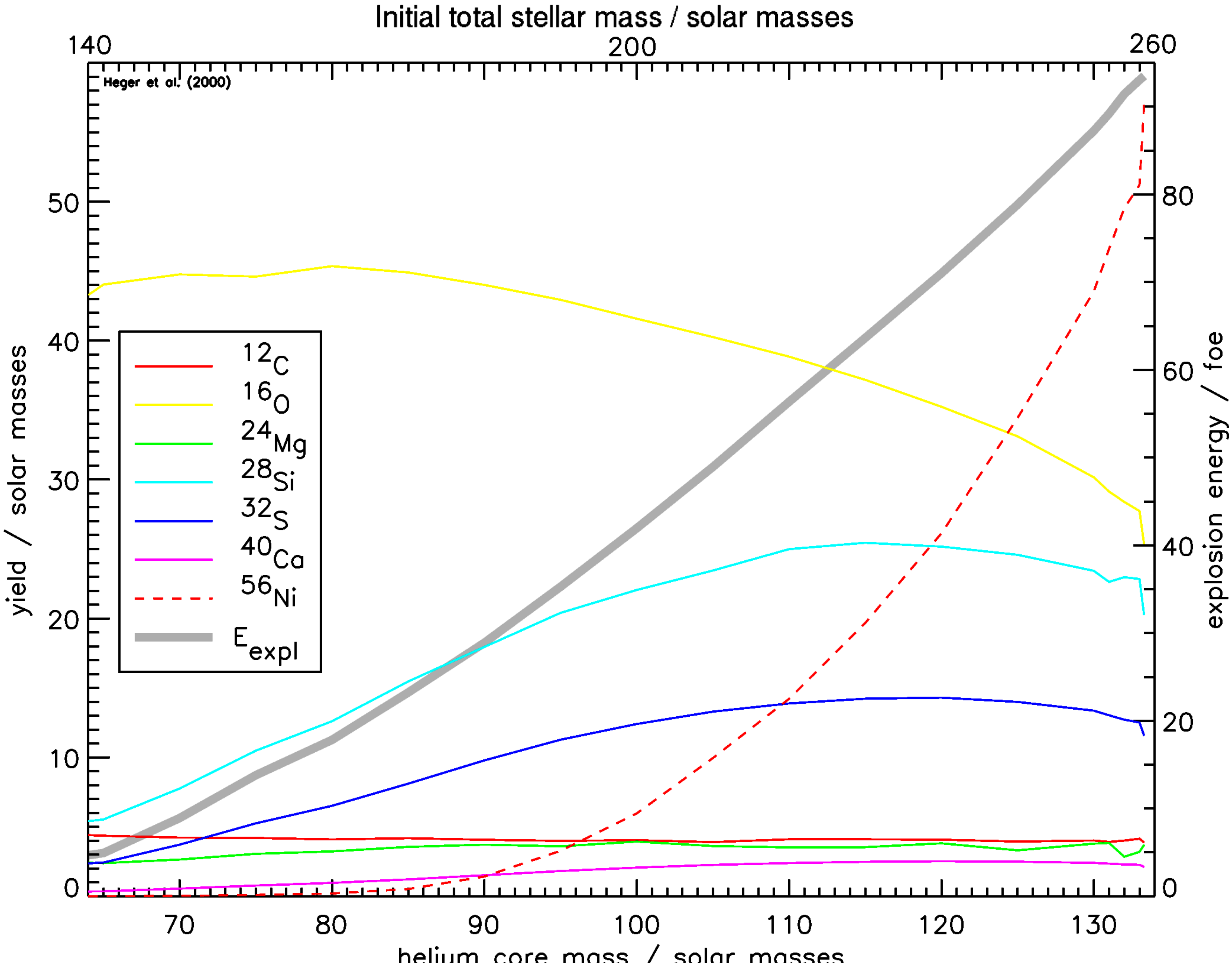


Ejected "metals"

Pair-Instability Supernovae

Many studies in literature since more than 3 decades, e.g.,
Rakavy, Shaviv, & Zinamon (1967)
Bond, Anett, & Carr (1984)
Glatzel, Fricke, & El Eid (1985)
Woosley (1986)

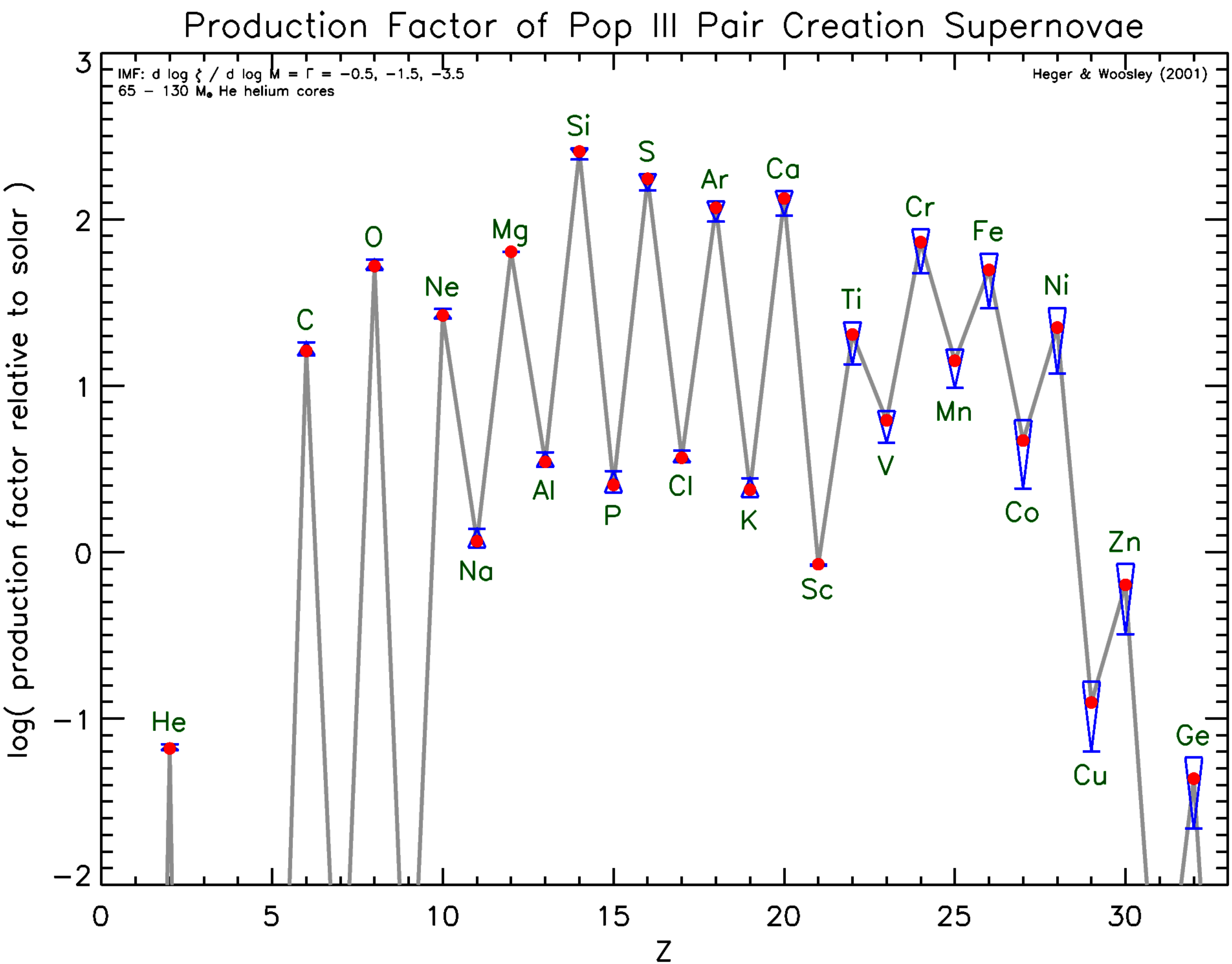
Some recent calculations:
Umeda & Nomoto 2002
Heger & Woosley 2002



Initial total stellar mass / solar masses
140
200
260
Heger et al. (2000)
yield / solar masses
50
40
30
20
10
0
80
60
40
20
0
explosion energy / foe
12C
16O
24Mg
28Si
32S
40Ca
56Ni
Eexpl
70
80
90
100
110
120
130
helium core mass / solar masses

Bright Supernovae at the edge of the Universe

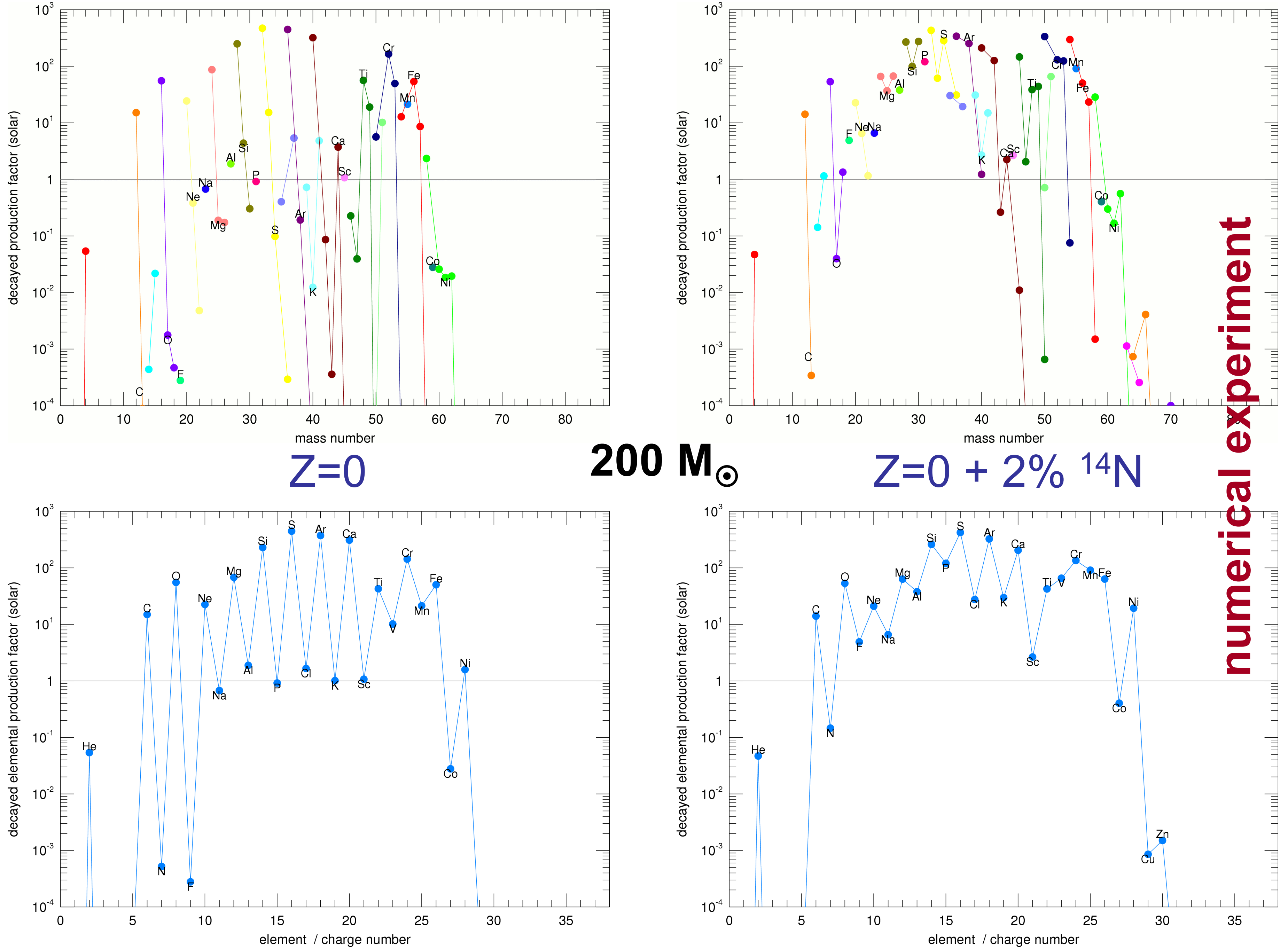
- Explosion energy from 4×10^{51} up to 10^{53} erg
  (~100x that of “normal” supernovae)
- Up to 90 solar masses of radioactive ^{56}Ni
  (~150x that of “normal” supernovae)
- Assuming that 10^{-6} of all baryons go into 250 $M_{\odot}$ stars, at z=20, the event rate could be up to **one every 6 sec**
  (for Ω_{Λ}=0.7, Ω_{matter}=0.3, H_0=65km/s/Mpc, Ω_b=0.02/h^2=0.047)
- They would last about 10 yr in observer frame
  (large mass ➔ long intrinsic light curve, high redshift)
- This is ~1000 of such objects per square degree at any time
  (assuming no extinction)
- They are intrinsically brighter than Type Ia SNe (bolometric)
- Only observable in the near infrared
  (due to absorption by neutral hydrogen short of 1215Å, redshifted by a factor 1+z)



Production Factor of Pop III Pair Creation Supernovae
IMF: d log ζ / d log M = Γ = −0.5, −1.5, −3.5
65 − 130 M☉ He helium cores
Heger & Woosley (2001)
log(production factor relative to solar)
Z
He
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge

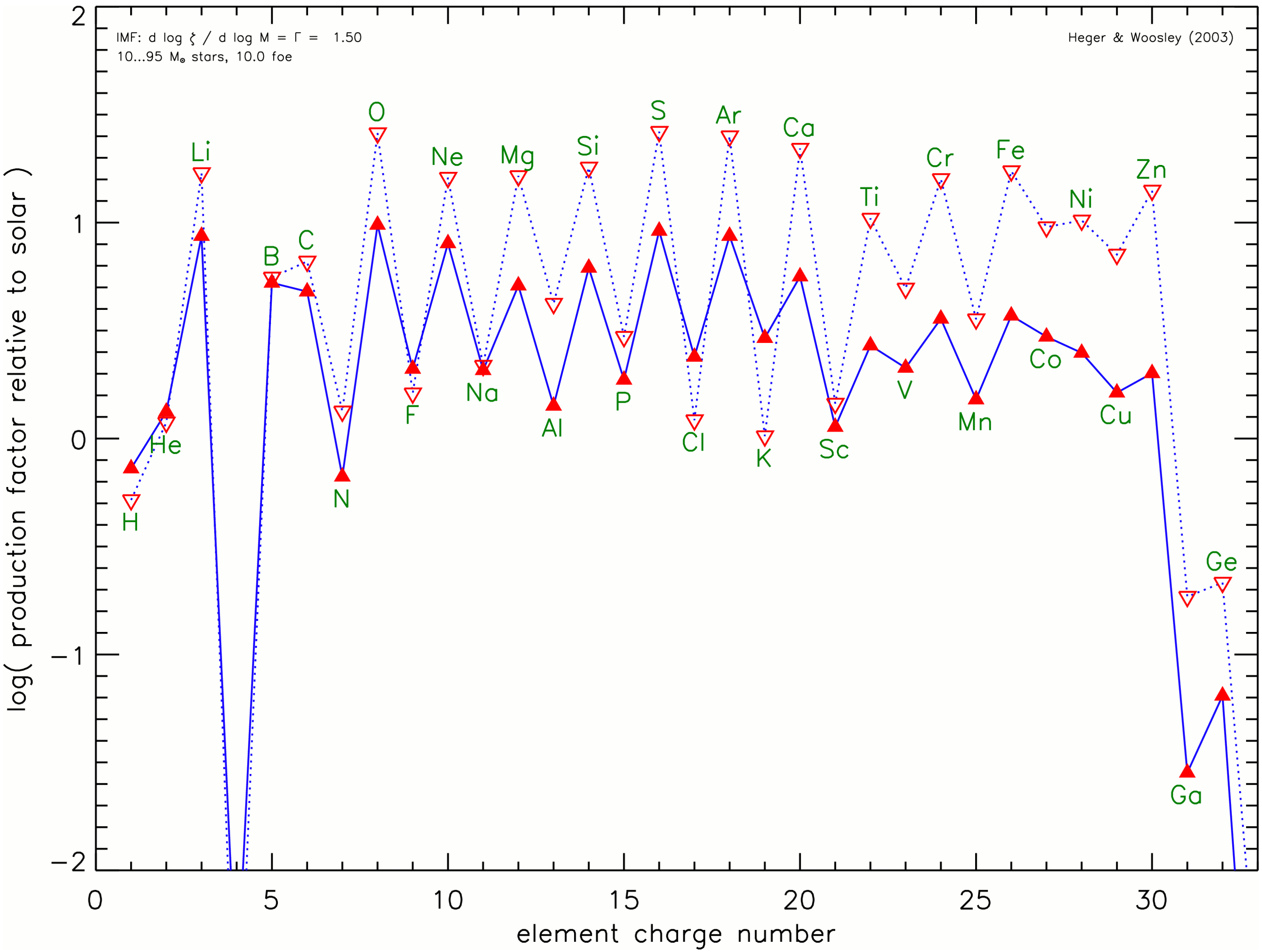
➔Problem:

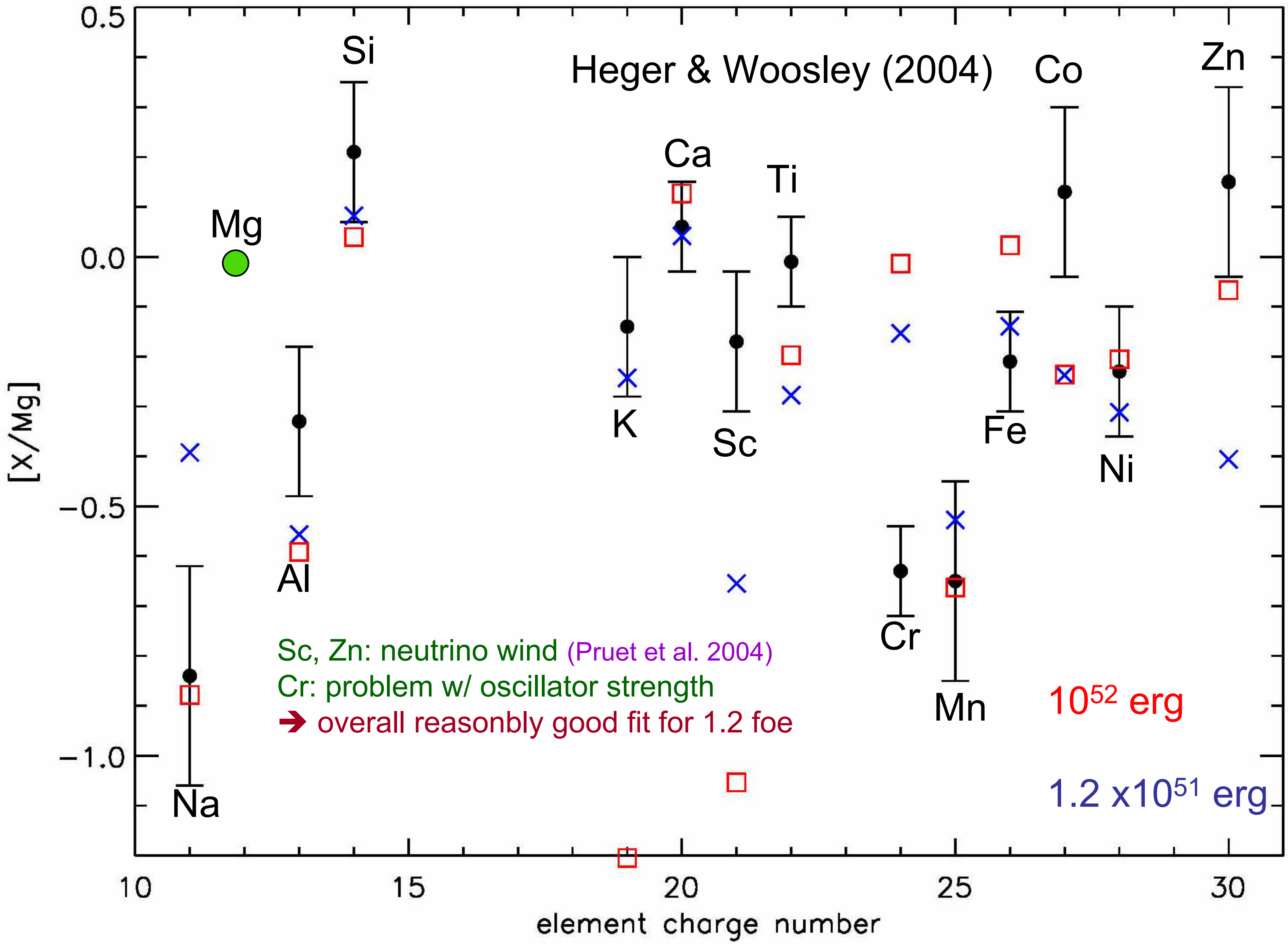
Pair-Instability Supernovae do not reproduce the abundances as observed in very metal poor halo stars!



200 $M_\odot$
Z=0
Z=0 + 2% ^{14}N
numerical experiment
decayed production factor (solar)
mass number
decayed elemental production factor (solar)
element / charge number

1.2 foe and 10 foe explosions



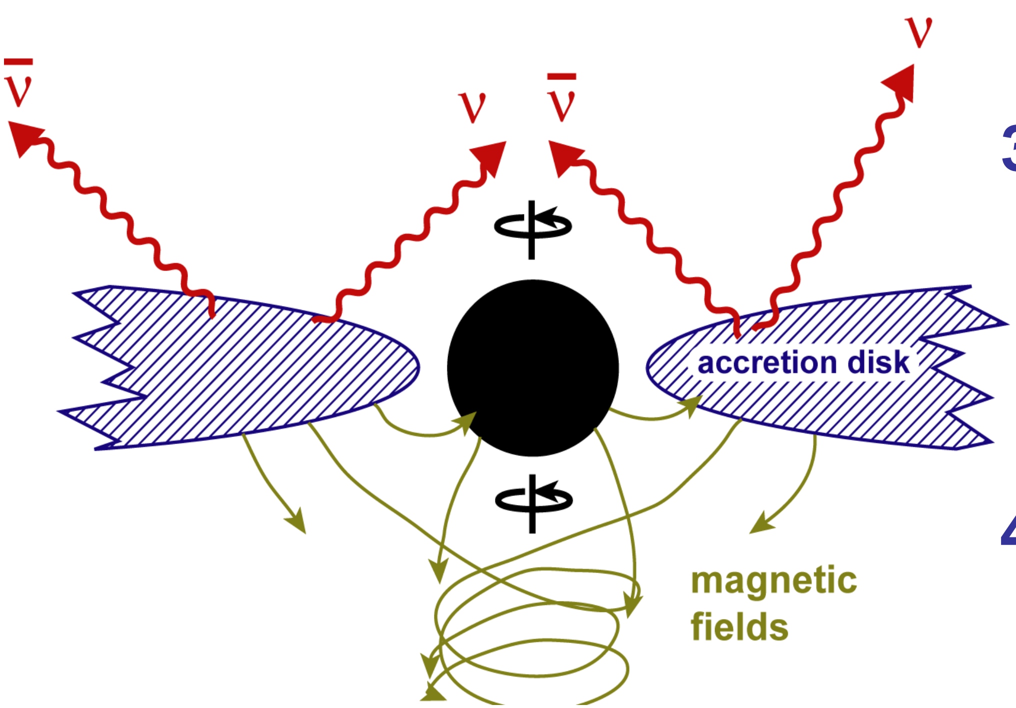


(Data from Cayrel et al. 2003, A&A, 416, 1117)

How else can massive stars explode?

$25M_\odot < M < 100M_\odot$,
$M > 250M_\odot$

The “Collapsar Engine”



1. black hole forms inside the collapsing star
2. The infalling matter forms and accretion disk
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

--- SPECULATION ---

Why don't we see the Pair-SN abundance pattern?

1) **Have very massive stars really formed? How rarely?** (feedback)

2) Where to find pure pair-SN ejecta?

- Where did stars that formed from the 2SN ejecta end up in the present Galaxy?
    - ↔ Should we really **expect** to find such halo stars?
    - ↔ Top-heavy IMF till $Z \approx 10^{-4} Z_{\odot}$?

3) **Modification to Pop III star nucleosynthesis?**

- Are 2SNe ***the*** (only) contribution to UMP stars, Ly_{α} forest, DLAs, …? Or were there other contributions?
- large contribution by 2nd generation primordial stars (poster II P4 by Brian O'Shea)

Summary

Due to their unique composition, the birth, life and death of the first stars is very different from later generations:

- Even stars of several 100 solar masses might survive
  (if rotating slowly, no winds, no pulsational instability)
- They can encounter the pair-instability, **but**:
  - strong odd-even effect that has not been observed to date
  - No heavy elements beyond iron group produced
  - No *r*-process, no *s*-process – **not *directly* observed to date**
- Strong odd-even abundance pattern in pair-SNe

➔ No compelling observational evidence for $M \geq 140\ M_{\odot}$ stars